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This grant supported a range of theoretical work on topics in neural networks, learning theory, dynamical systems and optimization. We summarize the achievements below and give a list of the relevant publications.

(a) LIST OF ACHIEVEMENTS.

It is convenient to divide the work into four parts: (i) dynamical systems models of computation, (ii) learning and reasoning theory, (iii) clocked neural networks and quantum computing, and (iv) statistical physics models of neural networks.

1. Dynamical System Models of Computation.

We found a formalism for describing the dynamics of hybrid systems and studied their capabilities as computers. Our models allow us to look at certain basic processes such as analog to digital conversion, in an abstract way emphasizing the fact that digital representations need to be robust whereas analog ones are continuously variable. Through the study of these models we are able to see certain problems in computer science and signal processing in a common framework. We have found certain classes of differential equations with inputs whose responses have readily identifiable characteristics which depend only on topological aspects of the inputs and not on the detailed behavior of the input. These systems can be thought of as defining automata and are capable of performing certain computations in an extremely robust way. See references [1-7].

2. Learning and Reasoning Theory.

We proved that many models of reasoning, and approximate reasoning, commonly used in Artificial Intelligence are computationally infeasible, in the sense of being NP-complete. We put complexity bounds on approximate reasoning for classes of propositional formulae. Learning theory was applied to learning visual concepts. A book, "Circuits of the Mind", was published describing a theory of the brain based on neuron-like elements, called *neuroids* (see reference [21]). This book emphasized the importance of considering the computational feasibility of algorithms and of exploiting the high degree of connectedness in the brain. The book included models for cognitive abilities such as learning (with or without a teacher), memorization, and reasoning. In addition it outlined the development of a theory for learning to reason. See references [8], [10-14], [16-18], [20-21].

3. Clocked neural networks and quantum computing.

We completed an analysis of a new clocked neural network architecture - competitive neural networks - optimized for visual pattern recognition. Small groups of fully interconnected electronic elements are used to recognize elemental pattern features. The state of each small group, i.e. the most favored features, are then compared over larger distances, using relatively few long range interconnections, in order to stitch together larger objects. In a series of two long papers (references [23-24]) we presented a detailed analysis of the global stability of competitive networks, and analyze the performance of associative memory using this architecture. We obtained "phase diagrams" with regions of guaranteed stability, which can be used for system design. These analytical results were in good agreement with numerical stability. We constructed double and triple quantum dots with tunable coupling, using electron beam patterned gates on top of GaAs/AlGaAs heterostructures. Such devices can be regarded as artificial molecules with tuneable molecular coupling. The Coulomb blockage is used in low temperature measurements to determine the existence and energetics of molecular electronic states, which are superpositions of the electron states on the separate quantum dot sites. A strong splitting of Coulomb blockage conductance peaks into two (and three) peaks as the interdot tunneling is increased for double (and triple) dots confirm the existence of coherent molecular states [25]. This project is being transferred to other sources of funding. We plan measurements of the molecular states for other interconnection topologies, and plan to test the sensitivity of coherent states to electromagnetic radiation. See references [22-25].

4. Statistical Physics models of neural networks.

We used mean field analysis to understand the properties of texture models near their phase transitions temperatures. We developed a new approach to self-organization of early vision and

showed a relation to the influential work of Becker and Hinton. We showed that algorithms based on statistical physics could be applied to calculate robust principal components. We analyzed deterministic annealing, related it to other optimization algorithms, and proved convergence bounds for the linear assignment problem. We obtained convergence bounds for learning using Radial Basis functions and related networks. We showed that realistic neuronal models could act as content addressable memories. It was demonstrated that statistical physics algorithms could be used to perform robust principal component analysis. See references [9], [15], [19], [26-32].

(b) PUBLICATIONS.

- [1] A.M. Bloch, R.W. Brockett and T.S. Ratiu. "On the Geometry of Saddle Point Algorithms", *Proceedings of the 1992 Conference on Decision and Control*, IEEE, 1992.
- [2] R.W. Brockett. "Analog and Digital Computing", in *Future Tendencies in Computer Science, Control and Applied Mathematics*, A. Bensoussan and J-P. Verjus (Eds.) LNCS, vol. 653, Springer-Verlag, Berlin, pp. 279-289. 1992..
- [3] A. Blum, R. Khardon, E. Kushilevitz, L. Pitt and D. Roth, "On Learning Read- k -Satisfy- j DNF". In *Proc. Seventh ACM Conference on Computational Learning Theory*, pp 317-326, July 1994.
- [4] R.W. Brockett, "Hybrid Models for Motion Control Systems", in *Perspectives in Control*, (H. Trentelman and J.C. Willems, Eds.), Birkhäuser, Boston, 1993, pp. 29-54.
- [5] R.W. Brockett. "The Double Bracket Equation as the Solution of a Variational Problem", in *AMS Fields Institute Series*, (A.M. Bloch, Ed.), American Mathematical Society, 1994, pp.69-76.
- [6] R.W. Brockett. "Differential Equations and Matrix Inequalities on Isospectral Families", *Linear Algebra and Its Applications*, Vol. 203-204, pp. 189- 207, (1994).
- [7] R.W. Brockett. "Dynamical Systems and Their Associated Automata", *Systems and Networks: Mathematical Theory and Applications—Proceedings of the 1993 MTNS*, (U. Helmke, R. Mennicken, and J. Saurer, Eds), Akademie-Verlag, Berlin, Vol. 77, 1994, pp. 49-69.
- [8] K. Daniels, V.J. Milenkovic and D. Roth, "Finding the Maximum Area Axis-Parallel Rectangle in a Simple Polygon". *Computational Geometry: Theory and Applications*. To appear, 1995.
- [9] I.M. Elfadel and A.L. Yuille. "Mean-Field Phase Transitions and Correlation Functions for Gibbs Random Fields". *Journal of Mathematical Imaging and Vision*, Vol. 3, No. 2. pp 167-186. June. 1993.
- [10] R. Khardon and D. Roth. "Exploiting Relevance in Model-Based Reasoning". In AAAI Fall symposium on Relevance, Nov, 1994.
- [11] R. Khardon and D. Roth. "Reasoning with Models". In *Proc. AAAI94, the National Conference on Artificial Intelligence*, pp 1148-1153. August, 1994.
- [12] R. Khardon and D. Roth. "Learning to Reason". In *Proc. AAAI94, the National Conference on Artificial Intelligence*, pp 682-687. August, 1994.
- [13] R. Khardon and D. Roth. "Learning to Reason". To appear in *Journal of the Association for Computing Machinery*, 1995.
- [14] E. Kushilevitz and D. Roth. "On Learning Visual Concepts and DNF Formulae" *Machine Learning*. To appear, 1995.
- [15] M. Matsugu and A.L. Yuille. "Spatio-temporal information storage in a content addressable memory using realistic neurons". *Neural Networks*. Vol. 7, mo. 3, pp 419-439. 1994.
- [16] D. Roth. "On Learning Visual Concepts and DNF Formulae". In *Proc. The Sixth ACM Conference on Computational Learning Theory*. July 1993.
- [17] D. Roth. "On the Hardness of Approximate Reasoning". In *Proc. 13th International Joint Conference on Computer Vision*, pp 613-618. August 1993.
- [18] D. Roth. "On the Hardness of Approximate Reasoning", *Artificial Intelligence Journal*. To appear, 1995.
- [19] S.M. Smirnakis and A.L. Yuille. "Neural Implementation of Bayesian Vision Theories by Unsupervised Learning". In *Proceedings on Computation and Neural Systems*. Monterey,

California. 1994.

[20] L.G. Valiant. "Why BSP Computing?". In *Proc. 7th International Parallel Processing Symposium*. IEEE Computer Society Press. Los Alamitos, CA. 1993.

[21] L.G. Valiant. "Circuits of the Mind". Oxford University Press. 1994.

[22] F.R. Waugh, C.M. Marcus, and R.M. Westervelt, "Nonlinear Dynamics of Analog Associative Memories". In *Neural Associative Memories*, ed. by M. Hassoun. Oxford University Press, Oxford, 1992.

[23] F.R. Waugh and R.M. Westervelt, "Analog Neural Networks with Local Competition: I Dynamics and Stability". *Phys. Rev. E* **47**, 4524. June 1993.

[24] F.R. Waugh and R.M. Westervelt, "Analog Neural Networks with Local Competition: II Applications to Associative Memories". *Phys. Rev. E* **47**, 4537. June 1993.

[25] F.R. Waugh, R.M. Westervelt, K. Campman and A.C. Gossard, "Single-Electron Charging in Double and Triple Quantum Dots with Tuneable Coupling". To appear in *Phys. Rev. Lett.* 1995.

[26] L. Xu, A. Krzyzak, and A. Yuille. "On Radial Basis Function Net and Kernel Regression: Approximation Ability, Convergence Rate and Receptive Field Size" *Neural Networks*. Vol. 7. No. 4. pp 609-628. 1994.

[27] L. Xu and A.L. Yuille. "Self-Organization for Robust Principal Component Analysis by the Statistical Physics Approach". In *Proceedings Neural Information Processing Systems: Natural and Synthetic*. 1993.

[28] L. Xu, and A.L. Yuille. "Robust Principal Component Analysis by Self-Organizing Rules Based on Statistical Physics Approach". *IEEE Trans on Neural Networks*. Volume 6, Number 1, pp 131-144. January. 1995.

[29] A.L. Yuille and J.J. Kosowsky. "A Mathematical Analysis of Deterministic Annealing." In *Artificial Neural Networks with Applications in Speech and Vision*. Ed. R.J. Mammone. Chapman and Hall. 1994.

[30] A.L. Yuille and J.J. Kosowsky. "Statistical Physics Algorithms that Converge" *Neural Computation*. **6**, pp 341-356. 1994.

[31] A.L. Yuille, S.M. Smirnakis and L. Xu. "Bayesian Self-Organization". In *Proceedings Neural Information Processing Systems: Natural and Synthetic*. 1993.

[32] A. L. Yuille, P. Stolorz and J. Utans. "Statistical Physics, Mixtures of Distributions and the EM Algorithm." *Neural Computation*. Vol. 6, No. 2. pp 334-340. 1994.